EFFECT OF SOLUTION TREATMENT TEMPERATURE ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A356 ALLOY

MUHAMAD AZRUL BIN AMIR

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UNIVERSITY MALAYSIA PAHANG

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ABSTRACT

Aluminum content in a vehicle is keep increasing around the globe due to the needs to reduce vehicle weight and increase fuel efficiency. The majority of the components are cast product which mostly casted from A356 alloy because of its excellent characteristics such as cast ability, high weight-to-strength ratio, good corrosion resistance and good weld ability compared to other types of alloy. Heat treatment is done to harness the full potential of cast A356 alloy and T6 is the commonly used heat treatment for this alloy. Most of the solution treatments (ST) study is done on sample having α-Al with dendritic structure. The specimen was cast using low pouring temperature (LPT) method which produces equiaxed α-Al structure. The objective of this research is to study the effect of ST temperature on microstructure and mechanical properties of A356 (Al7Si0.3Mg) aluminum alloy. The specimen undergone ST for two (2) hours at three different temperatures (530 °C, 540 °C, and 550 °C), quenched in water at room temperature, and artificial aged for six (6) hours at 170 °C. Mechanical properties of A356 aluminum alloy were investigated by utilizing tensile test and hardness test, the later is the main interest of this study. The relation between size, shape, and distribution of Si particle and the alloy's mechanical properties were investigated. It was found that Si particle size, shape, and dispersion affect the mechanical properties of cast A356 alloy. Higher ST temperature produce smaller and more globular Si particle before completing T6 heat treatment. Elongation decreases while ultimate tensile strength (UTS) increased as ST temperature increased from 530 °C to 550 °C. A356 aluminum alloy specimen solution treated at 530 °C have comparable hardness compared with specimen ST at 540 °C before and after artificial ageing (AA) - complete T6 heat treatment - with higher elongation and lower energy usage as added benefit.

ABSTRAK

Kandungan aluminium di dalam kenderaan terus meningkat di seluruh dunia berikutan keperluan untuk mengurangkan berat kenderaan dan meningkatkan kecekapan bahan api. Kebanyakan komponen adalah produk tuangan yang kebanyakannya dituang daripada aloi A356 kerana ciri-cirinya yang cemerlang seperti keupayaan tuangan, nisbah berat kepada kekuatan yang tinggi, ketahanan terhadap kakisan yang baik dan keupayaan kimpal yang baik berbanding dengan lain-lain jenis aloi. Rawatan haba dilakukan untuk mendapatkan potensi penuh aloi A356 tuang dan T6 ialah rawatan haba yang biasa digunakan untuk aloi ini. Kebanyakan kajian rawatan larutan (ST) dilakukan ke atas sampel yang mempunyai α-Al dengan struktur dendritik. Spesimen yang dituang menggunakan kaedah tuangan suhu rendah (LPT) menghasilkan α-Al dengan struktur yang mempunyai dimensi yang hampir sama dalam semua arah. Objektif kajian ini adalah untuk mengkaji kesan suhu ST ke atas mikrostruktur dan sifat mekanik aloi aluminium A356 (Al7Si0.3Mg). Spesimen melalui rawatan larutan selama dua (2) jam pada tiga suhu yang berbeza (530 °C, 540 °C, dan 550 °C), padam dalam air bersuhu bilik, dan penuaan tiruan selama enam (6) jam pada suhu 170 °C. Sifat mekanikal aluminium aloi A356 telah disiasat menggunakan ujian ketegangan dan ujian kekerasan, dimana ujian kekerasan dijadikan sebagai tumpuan utama dalam kajian ini. Hubungan diantara saiz, bentuk, dan serakan zarah Si dengan sifat mekanikal aloi ini telah disiasat. Kajian mendapati bahawa saiz zarah, bentuk, dan serakan zarah Si memberi kesan kepada sifat-sifat mekanik aloi A356 tuang. ST pada suhu tinggi menghasilkan zarah Si yang lebih kecil dan lebih globular sebelum melengkapkan rawatan haba T6. Pemanjangan berkurangan manakala kekuatan tegangan mutlak (UTS) bertambah apabila suhu ST bertambah daripada 530 °C ke 550 °C. Spesimen aluminium aloi A356 yang melalui rawatan larutan pada suhu 530 °C mempunyai kekerasan yang setanding berbanding dengan spesimen yang dirawat pada suhu 540 °C sebelum dan selepas penuaan tiruan (menamatkan proses rawatan haba T6) dengan pemanjangan yang lebih tinggi dan penggunaan tenaga yang lebih rendah sebagai manfaat tambahan.

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LIST OF ABBREVIATION

530 ST	Solution treated at 530 °C, room temperature water quench
530 T6	Solution treated at 530 °C, room temperature water quench, artificial ageing
540 ST	Solution treated at 540 °C, room temperature water quench
540 T6	Solution treated at 540 °C, room temperature water quench, artificial ageing
550 ST	Solution treated at 550 °C, room temperature water quench
550 T6	Solution treated at 550 °C, room temperature water quench, artificial ageing
AA	Artificial ageing
AAA	American Aluminum Association
AC	As-cast
Al - Si	Aluminum - Silicon
ASTM	American Society for Testing and Material
DAS	Dendrite arm spacing
GP	Guinier-Preston
HV	Vickers' hardness number
LPT	Low pouring temperature
NP	Normal pouring
SDAS	Secondary dendrite arm spacing
ST	Solution treatment
UTM	Universal Testing Machine
UTS	Ultimate tensile strength
YS	Yield strength

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Over the years, aluminum content in a vehicle is keep increasing around the globe due to the needs to reduce vehicle weight and increase fuel efficiency. The majority of the components are cast product which, mostly casted from A356 alloy. A356 alloy become the favorite type of alloy to be cast because of its excellent characteristics over other type of alloy such as cast ability, high weight-to-strength ratio, good corrosion resistance and good weld-ability. Most of the cast component in a vehicle such as cylinder head for example, favors hardness over tensile strength.

Dendritic α-Al structure is produced by casting A356 alloy using normal pouring (NP) method, which is pouring melted alloy at high temperature. In the other hand, the low pouring temperature (LPT) method, which is pouring melted alloy at low temperature near its liquidus temperature produce α-Al with equiaxed or globular structure. Equiaxed structure reduce forming resistance, thus, more complicated component can be cast. In case of permanent mold and die casting, LPT method prolonged the mold service life.

Heat treatment is done to harness the full potential of cast A356 alloy. Study by Möller et al. (2008) shows long solution treatment time provide low hardness and short solution treatment provide high hardness. The distribution, morphology, volume fraction, degree of Si particle modification, composition of phases of the as-cast microstructure, along with the ST parameters (temperature, time) chosen determine the successfulness of ST.

1.2 IMPORTANT OF RESEARCH

Unsuitable ST regime will waste the effort of producing equiaxed/globular α-Al structure of sand cast A356 alloy. If ST temperature is too low, the alloying elements will not have complete dissolution and become unavailable for precipitation hardening and too high ST increase the cost due to high energy usage than is necessary.

1.3 PROBLEM STATEMENT

Most of ST studied was based on dendritic α-Al structure like what was done by a number of researchers such as Sjölander et al. (2008) for example. The objective of ST is to homogenize the alloying element (Si) and spheroidize the eutectic Si particle. The LPT method produced equiaxed α-Al structure, in which the alloying element is spread throughout the aluminum in a much higher degree compared to NP which produces dendritic α-Al structure. This means that LPT helps in homogenizing the alloying element to some extent. ST will further homogenize the alloying element – with less work to do thanks to the LPT method; therefore its priority now is to spheroidize the eutectic Si particle. Therefore, the ST regime needs to be reviewed for α-Al having equiaxed or globular structure.

1.4 PROJECT OBJECTIVE

To investigate the effect of solution treatment temperature on microstructure and mechanical properties of A356 alloy

1.5 PROJECT SCOPE

i. Casting of A356 alloy by sand casting method
ii. Heat Treatment of A356 alloy
iii. Microstructure study
iv. Mechanical properties analysis namely hardness, tensile strength,% elongation

1.6 RESEARCH FLOW CHART

Figure 1.1 shows the process flow chart along the study. This provides clear image of the research flow of this study.

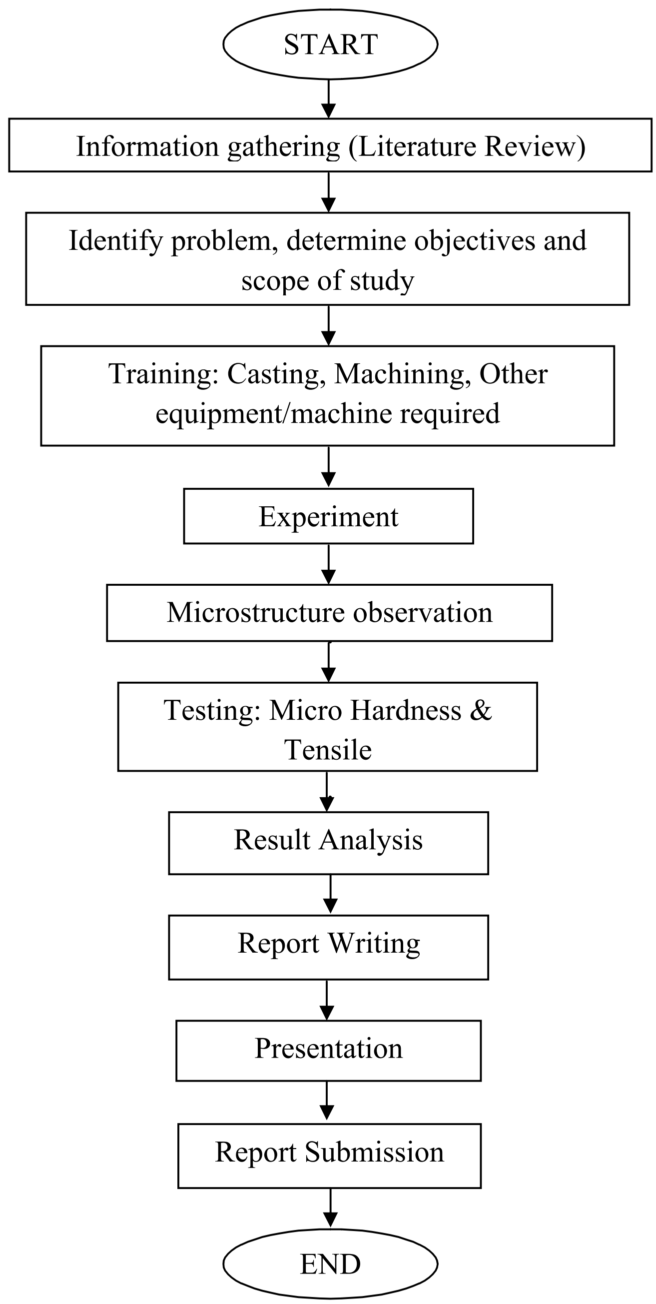

Figure 1.1: Research flow diagram

CHAPTER 2

LITERATURE REVIEW

2.1 ALUMINUM AND A356 ALLOY

2.1.1 Aluminum

Aluminum made up about 8% of the earth crust and can be found in most rocks, clay, soil, and vegetation. It occurs in nature only as compounds with oxygen and other elements, never in the metallic form. The availability of products based on aluminum depends on two chemical processes developed in the late nineteenth century. In the Bayer process, alumina (Al_2O_3) is extracted from bauxite – rock in which aluminum hydroxides have been highly concentrated by weathering. In the hall/herald process, molten cryolite (Na_3AlF_6) is used to dissolve alumina, and the solution is then electrolyzed to obtain aluminum metal. Aluminum is distinguished from other metals by its low density, high surface reflectivity, and high electrical and thermal conductivity (Shuey et al., 1993).

Aluminum-silicon (Al-Si) alloys are gaining popularity compared to other type of aluminum alloys used in automotive and aerospace applications, due to to their higher strength-to-weight ratios, better cast ability, better wear resistance, and better surface finish. An increase in cast Al-Si alloy component in vehicle is seen due to the need to produce component with higher strength-to-weight ratios. A near-net-shape process is once more gaining interest due to the need to conserved energy, manufacturing costs, material, and section thickness which is difficult to achieve via sand-casting processes. The aluminum alloy is the second most popular casting materials after ferrous castings in term of tonnage usage. The American Aluminum

Association (AAA) has divided the aluminum alloys into groups based on their alloying element.

Al-Si is identified as the 3XX.X series of aluminum alloys by the AAA, which makes up 80 to 90% of the total cast aluminum, produced worldwide (Gruslezki et al., 1990, Campbell, 2003, ASM, 1990). The characteristics of 3XX.X series are heat treatable, excellent fluidity, high-strength, approximate ultimate tensile strength range: 130 to 275 MPa (20–40ksi) and readily welded.

The 3XX.X series is one of the most widely used aluminum alloy in casting because the high silicon content contribute to its fluidity and flexibility. Variety of high strength option could be achieved via heat treatment due to their good response to heat treatment. In addition, variety of techniques can be used to cast the 3XX.X series, from the simple sand or die casting to the complicated permanent mold, investment castings, and the newer thixocasting and squeeze casting technologies.

Among the widely used aluminum alloys are 319.0 and 356.0/A356.0 for sand casting; 360.0, 380.0/A380.0 for permanent mold casting; 390.0 for die casting; and 357.0/A357.0 for many types of casting, including, especially, the relatively newly commercialized squeeze cast technologies.

2.1.2 A356 Alloy

In recent years, the use of Al–Si–Mg casting alloys, especially the A356 (Al7Si0.3Mg) has increased in the automotive industry due to its excellent cast ability, corrosion resistance and good mechanical properties in the heat-treated condition, hot tearing resistance, good weld ability and high strength to weight ratio (Wang et al., 2001). A356 is a hypoeutectic Al-Si alloy with a wide range of applications in the automotive and avionics industries. A356 is one of the most common aluminum alloys used in near-net-shape process because of its advantages of high fluidity and good cast ability due to the high content of Al-Si eutectic (Zhang et al., 2008). Example of application of sand cast A356.0 alloy are automotive transmission cases, water-cooled cylinder blocks, flywheel housings, oil pans, various fittings and pump bodies. This alloy, after being heat treated under T6 heat treatment, is also applied in various marine applications where pressure tightness or corrosion resistance is major requirements.

2.2 SAND CASTING

Sand casting is one of the earliest metal forming processes used for manufacturing metal parts. It is a process of pouring molten metal into a sand mould with a cavity of the shape to be made and allowing it to solidify. The process of casting involves the basic operations of pattern making, sand preparation, molding, melting of metal, pouring in moulds, cooling, shake-out, fettling, heat-treatment finishing and inspection (Rao, 1996). Almost any shape, size, and metal can be cast using sand casting method by suitable molding and core-making technique. Sand casting provides a wide range of property selection for the finished cast-parts by suitable choice of alloy and heat-treatment.

2.2.1 Pattern

A pattern is a model used to make dimensionally accurate mould cavity in which liquid metal is later poured, to make a casting (Rao, 1996). Pattern could be made of wood, metal, plastic and rubber, wax and polystyrene, etc. The material needs to have characteristics such as lightweight for ease of handling and working, strong, hard and durable, easy to work, shape and join, easily available at low cost, easy to repair and having the ability to give good surface finish. A good pattern has the following characteristics (Rao, 1996):

- **a.** Dimensional accuracy to get high quality casting
- **b.** Strength to withstand ramming and abrasion of molding sand
- **c.** Rigidity to prevent distortion and warping through seasonal change over a long period of use.
- **d.** Good surface for easy removal from mould
- **e.** Proper color-code to indicate to the molder, information regarding final casting and precaution during molding.

f. Should help to increase molding productivity through suitable design and construction and achieve overall economy in molding.

2.2.2 Molding Sand

There are seven requirements of good molding sand as stated by Rao (1996):

a. Refractoriness

Ability of the molding sand to withstand high pouring temperature of molten metal without itself being partially melted and fuses with the liquid metal, which could results in a very rough sand-fused casting surface.

b. Chemical Resistivity

The sand used for molding should be inert and not react chemically with the molten metal/alloy being poured into it.

c. Strength With Proper Binder

When combined with proper binder, the sand should develop adequate cohesion among its grains to be able to form and stay as a mould, withstand movement and handling of mould before pouring. It also should be able to withstand the compressive and erosive force by the liquid metal while filling in the mould cavity

d. Permeability

The ability to let gases and vapors produced from the pouring of molten metal to escape by having sufficient porosity.

e. Surface Finish

The smoothness of the casting depends on the fines of the sand grain. Good surface finish is necessary to avoid costly finishing operations.

f. Flow Ability

The capacity of molding sand to flow to different corners and intricate details in mould without much special effort to ram is a useful requirement of molding sand.

g. Collapse Ability

The sand should be able to peel off and disintegrate easily so that the cooled casting can be taken out and finished. In addition, sand having good collapse ability reduces the fettling and finishing cost.

h. Availability and Economy

2.2.3 Pouring Temperature

The grain size, secondary dendrite arm spacing (SDAS), interdendritic porosities, and structure of eutectic silicon affect the mechanical properties of Al–Si alloys (Kumai et al., 1996, Zhang et al., 1999, Atxaga et al., 2001). To improve the mechanical properties of Al-Si alloys, interest is now directed to make the as-cast microstructure to be finer. Common practice is to add grain refiner and modifier during melting to improve the mechanical properties of Al–Si casting alloys (Mohanty et al., 1996, Murty et al., 2002, Hegde et al., 2008).

Wang et al. (2011) found that low pouring temperature produced equiaxed α-Al structure, maximum microstructure refining effect could be obtained especially by the over melt thermal treatment. The refinement is caused by the nuclei multiplication in the melt. In addition, the higher cooling rate does little change on the morphology of eutectic silicon. Due to the refinement of the grain size, the silicon particle size also becomes finer. The tensile properties of the alloys improved, the alloy's UTS and elongation increased because of the refinement of the grain size and eutectic silicon. Apart from the increase in nucleation rate, the LPT also contribute to the growth of grains in globular form, resulting in microstructure to be fine, equiaxed and non-dendrite which are benefit for the tensile properties of AlSi7Mg alloy (Wang et al., 2002, Easton et al., 2006).

Both Mao et al. (2001) and Srinivasan et al. (2006) were in good agreement that LPT produce finer grain. It is clear that DAS increases with increase in pouring temperature and this (increase of DAS) will reduces the mechanical properties of the alloy (Srinivasan et al., 2006).

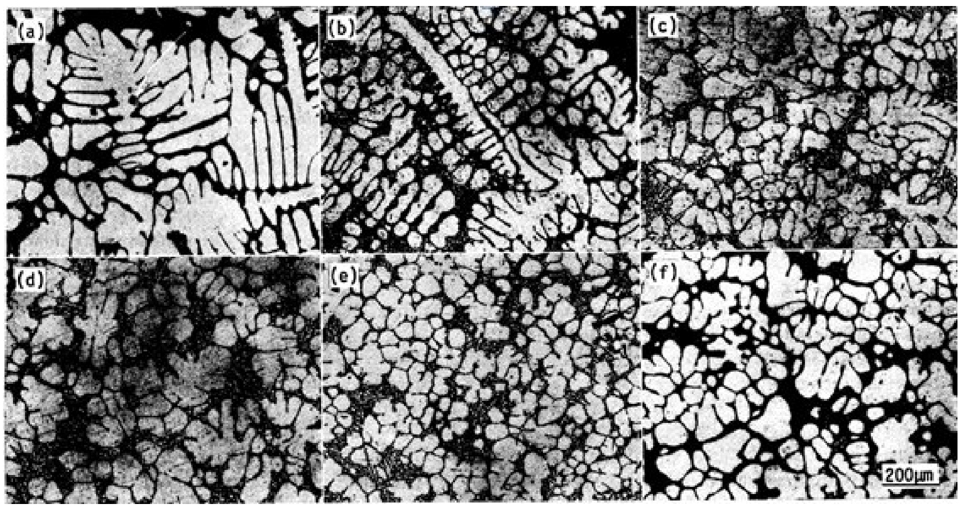

Figure 2.1: Microstructure of Al7Si0.3Mg alloy samples poured at different temperature (a) 750, (b) 650, (c) 630, (d) 620, (e)615, (f)610 °C

Source: Mao et al. (2001)

2.3 T6 HEAT TREATMENT

According to Smith et al. (2009), heat treatment refers to any of the heating and cooling operations which purpose is to change the mechanical properties, morphology or the residual stress state of a metal product. The T6 heat treatment is the typical and the most common heat treatment applied to sand cast A356 aluminum alloy, the treatment consist of the following stages (Sjölander et al, 2010):

1. Solution treatment at a relatively high temperature.
2. Quenching
3. Age hardening, either at room temperature (natural ageing) or at an elevated temperature (artificial ageing)

ASTM Standard B917-01 designates 6-12 hours at 540 °C, hot water quench, and then 2-5 hours at 155 °C for sand-cast A356. However, variations of a standard T6 heat treatment were investigated by researchers for Sr-modified and unmodified cast aluminum alloy A356 in terms of the effects on the mechanical properties.

2.3.1 Solution Treatment (ST)

ST is done at a high temperature, close to the eutectic temperature of the alloy; its purpose is to (Sjölander et al., 2010):

- Dissolve soluble phases containing Cu and Mg formed during solidification;
- Homogenize the alloying elements;
- Spheroidize the eutectic Si particles.

The time required for ST depends on a few factors such as the composition, structure, size and distribution of the phases present after solidification, and ST temperature (Sjölander et al., 2010, Smith et al., 2009). Most ST is carried out between 4 to 6 hours at 540 ^{o}C and is said to be the most optimum condition (Tensi et al., 1996, Shabestari et al., 2004, Cavaliere et al., 2004). ST of cast Al-Si-Mg alloys in the 400-560 ^{o}C range dissolves the hardening agents (Mg_2Si particles) into the α-Al matrix, reduces the micro-segregation of magnesium, copper, manganese, and other addition elements in aluminum dendrites, and spheroidize the eutectic silicon particles to improve the ductility (Davidson et al., 2002). The desired solution time and temperature, to a great extent, depend on the casting method, the extent of modification, and desired level of spheroidization and coarsening of silicon particles (Ma, 2006). According to Sjölander et al. (2010), homogeneous solid solution is formed when atoms leave the coarse particles formed during solidification and propagate into the Al-Si matrix and reduces the concentration gradient. The time required to homogenize the casting depends on the morphology of the diffusing atoms and the ST temperature (diffusion rate) as well as by coarseness of the microstructure (Sjölander et al., 2010). The time needed for spheroidize the eutectic Si particle is strongly depends on the ST temperature, shape and structure, and size of the eutectic Si particles in the as-cast (AC) condition. A Sr-modified sand-cast A356 alloy requires of 3-6 hours at 540 °C for optimal ST temperature (Shivkumar et al., 1990, Sjölander et al., 2010). The ST time can be reduced if the AC microstructure is finer (Sjölander et al., 2010).

The maximum temperature for ST of a metal must not exceed, when possible, its solidus temperature (Smith et al., 2009). Möller et al. (2008) investigated the effects of variations from T6 standard treatment on the hardness, ductility, and UTS of A356 alloy cast in a permanent mould with and without strontium modification. The main variables considered in the experiments were ST time and temperature. The as-cast samples were solution treated for various times (t=2, 4, 8, 16 and 32 hours) at 520 ^{o}C/540 ^{o}C and aged at 160 ^{o}C for 6.5. The highest hardness was obtained at a short ST time (2 hours) for both unmodified and modified A356, while the highest ductility wasn't achieved until the samples undergone 8 hours of ST at the same temperature.

2.3.2 Quenching

Quenching is done to suppress precipitate upon cooling the casting to room temperature from the high ST temperature (Sjölander et al., 2010). If the quench rate is high enough, the solute is retained in solid solution and high number of vacancies would also be retained (Sjölander et al., 2010). Conversely, too slow cooling rate cause the particle to precipitate heterogeneously at grain boundaries or at the dislocations; resulting in a decrease in the super saturation of solute and in the same time, resulting in lower maximum yield strength after completing the heat treatment. Weakness with rapid cooling is that the thermal stresses are induced in the casting. Water is the commonly used quenching media. Oil, salt baths and organic solutions can be used when a slower quench rate is required (Sjölander et al., 2010).

The most favorable characteristic of water as a quenching media is the exceptionally high quenching power due to its high specific heat of vaporization and high specific heat capacity. Other advantages of water, relative to production practices are (Luty, 1993):

- Non-flammability
- Low cost

- No hazards to health
- Easy scale removal
- No damages to the natural environment when drained to the wastes

In most practical cases, the water quenchants are used between 15 to 25 °C, although slightly lower or higher temperatures may occasionally appear to be favorable (Luty, 1993).

2.3.3 Artificial Ageing (AA)

Natural ageing occurs at room temperature while AA is at high temperatures. Ageing is done to obtain a uniform distribution of small precipitates, which contribute to high strength (Sjölander et al., 2010). According to ASM (1995) aging must be accomplished below the metastable solubility gap called Guinier-Preston (GP) zone solvus line. Li et al. (2004) reported the age hardening behavior of cast aluminum alloy A356. At higher aging temperature peak hardness was obtained at shorter aging times since the diffusion was faster at higher temperature (Li et al., 2004).

AA is typically done in the 150–210 °C range for Al-Si alloy. At these temperatures atoms can travel over larger distances and the precipitates formed during AA are normally much larger in size than Guinier-Preston (GP) zones (Sjölander et al., 2010). Al–Si–Mg alloys artificial aged at temperatures in the 170–210 °C range produce alloy with comparable level of strength (Rometsch et al., 2000). AA regimes at high temperatures for short periods are suggested to produce comparable mechanical properties obtained by AA regime at low temperature for long periods (Ber, 2000). Rometsch et al. (2000) also agreed that higher temperature can shorten the time required for AA

Sjölander et al. (2011) works with three different microstructure of Al-Si-Mg and he found that ageing at 170 °C produce comparable yield strength for the three coarsenesses of the microstructure as can be seen in Figure 2.3.

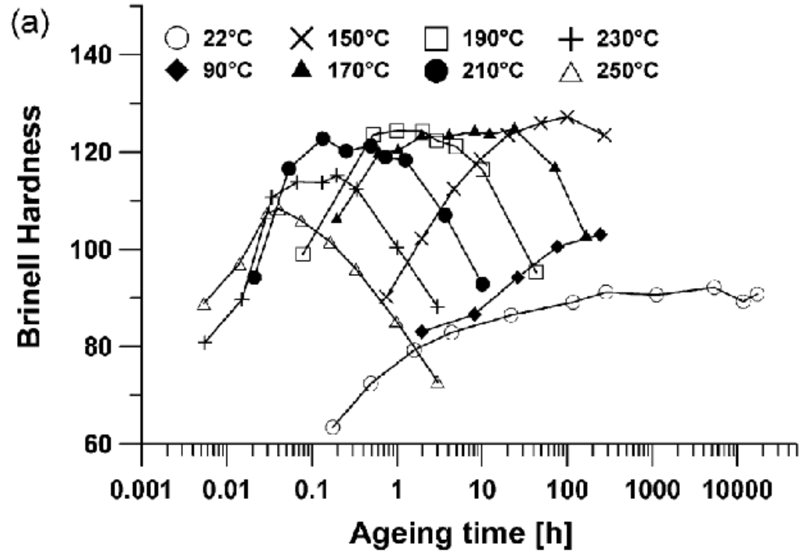

Figure 2.2: Hardness versus ageing time for different ageing temperature

Source: (Rometsch et al., 2000)

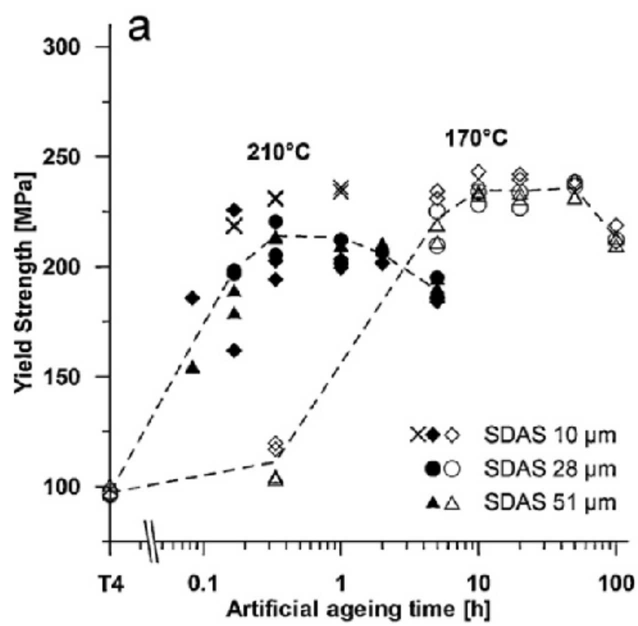

Figure 2.3: Artificial ageing time versus yield strength for different ageing time for different SDAS

Source: (Sjölander et al., 2011)

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION

In this chapter, the appropriate sequences of the works planned by the researcher in order to achieve the project objective and keeping it in the scope are presented. The experimental procedures, starting from the sample preparation until obtaining the data are described in details here on this chapter.

3.2 FLOW CHART

Figure 3.1 shows the experiment flow chart throughout this research paper starting from casting the A356 alloy until analyzed the data.